Measurement of magneto-optical properties of materials with a Kerr spectrometer

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The Kerr effect

The magneto optical Kerr effect arises when a magnetization in a material produces a difference in the complex index of refraction between left-circularly polarized (LCP) and right-circularly polarized (RCP) electromagnetic radiation. This circular birefringence will in turn lead to differences in the complex reflectivity coefficients for RCP and LCP light. There are two parameters that are commonly used to describe the Kerr effect. The Kerr angle is half of the complex phase difference between the circular reflection coefficients. The other is the ellipticity, which is related to the difference in magnitude of these coefficients. These parameters are known to be proportional to the magnetization. Incident linearly polarized light will be reflected with elliptic polarization in general. The major axis of this ellipse will be rotated relative to the orientation of the incident polarization by the Kerr angle.

On a very simplistic level, this effect is due to the presence of the magnetization breaking the isotropy of the motions of the electrons in the material via the Lorentz force. Incident linearly polarized light will accelerate the electrons in the material in the direction of polarization. The component of this motion perpendicular to the magnetization field will cause a Lorentz force. The resulting acceleration can have a component perpendicular to the incident polarization. This will then re-radiate with some extra component in this perpendicular direction.

A more complete description of the Kerr effect can be done in terms of dielectric and/or conductivity tensors. It can be shown that off diagonal terms are introduced in these tensors. Classically, the simple model above yields these off diagonal elements. An incident field in the x direction yielding an electric displacement in the y direction demands an off diagonal dielectric tensor. However, a classical description alone is not sufficient to model the effects seen in most actual materials. Quantum mechanical expressions exist for the elements of the dielectric and

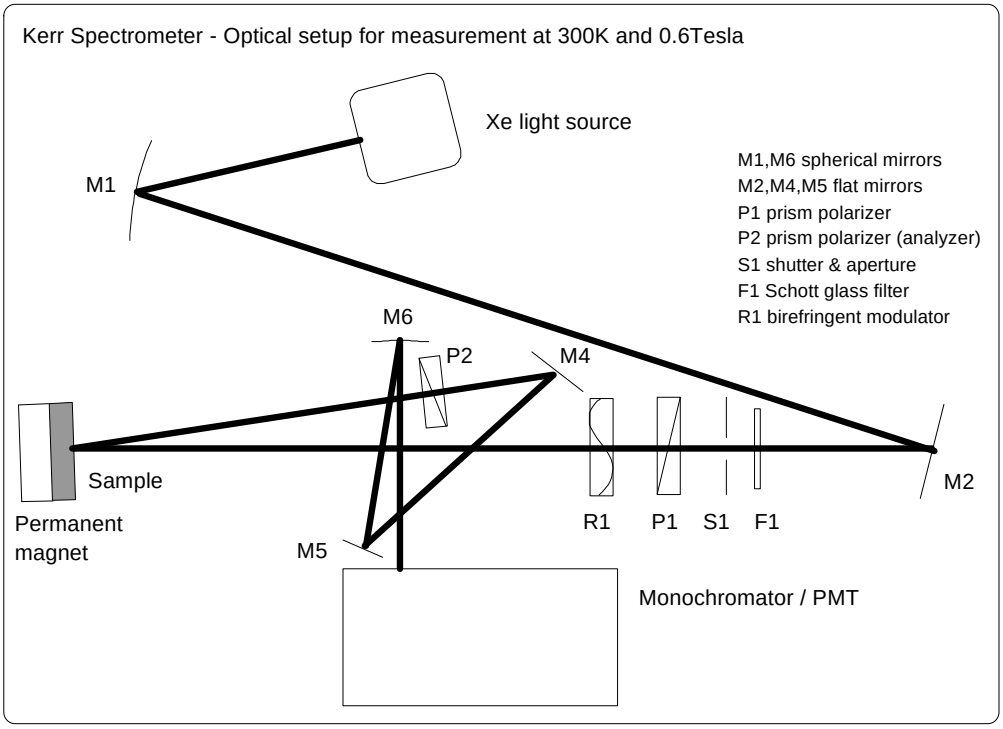
conductivity tensors. They can account for the effects of the band structure of the material, Zeeman splitting of these bands, spin-orbit coupling and electron-electron correlations. All of these effects contribute to the structure of the observed spectra of Kerr rotation vs. incident light wavelength.

Magneto-optic materials are technologically useful. Perhaps the most promising use is for magneto-optic recording. Information can be recorded by patterning the magnetization of a substrate, and then read back by observing the magnetization via the change in polarization of a reflected light beam. However, ferromagnetic materials have a small Kerr angle at room temperature, typically 0.1 degree or so at remanent magnetization. Recording spot size will be limited by magnetic domain size or the read beam diffraction, whichever is larger. Greater understanding of the underlying physics could result in new materials which will push these limitations in useful directions.

Measurements of the Kerr effect using a Kerr spectrometer will advance this cause. Not only is this instrument a powerful means of screening new materials for technological utility, but it is also a useful tool for examining model systems in an attempt to further theoretical understanding of magneto-optic effects.

The polar Kerr spectrometer

The polar Kerr spectrometer is designed to measure the Kerr rotation and ellipticity as a function of photon energy in the visible range. (1.5 - 5 eV) With the addition of a cryostat housing the sample and a superconducting magnet, measurements will also be made as a function of applied magnetic field and temperature.



Light from a Xe arc lamp is focused parallel and incident upon a prism polarizer. The transmitted light is then linearly polarized and incident upon a birefringent modulator. This is a piezoelectric crystal driven near its acoustic resonance at a frequency *f*. The induced strain in the modulator produces a variable retardation (phase shift) at the frequency *f* for the linear component of the light along the modulator's fast axis vs. the component along the slow axis. When the modulator is driven to produce a retardation amplitude of half the measured wavelength, the transmitted light has a polarization state that is alternating between linear and circular polarization at *2f*. This light is then incident on the sample and reflected to another prism polarizer, known as the analyzer. The beam is then collected with routing mirrors into a monochromator, where its intensity is detected with a photomultiplier tube. The optical path also includes a glass filter for reducing higher order leakthrough in the monochromator, and a shutter used to measure PMT dark currents. There may also be special routing mirrors before and after the sample, as well as cryostat windows if the sample is in the cryostat.

The PMT current at *f* and *2f* is measured using a lock-in heterodyne technique referenced to the modulator driving signal. These AC amplitudes are normalized by a measured DC signal from the PMT to yield the ellipticity and Kerr angle, respectively. The instrument is under computer control to change wavelengths and digitize signals to produce spectra of Kerr rotation and ellipticity vs. photon energy.

Instrument characterization

The group is still in the process of making the instrument work with the cryostat. Initial measurements made inside the cryostat did not reproduce the known Kerr spectra for Nickel, which has a peak rotation of about 0.15 degree or so. It was unknown how much of the problem was due to noise, and how much was due to systematic errors in the instrument. Standard deviation calculation for the data was added to the data collection program in an effort to determine this. Systematic error was found in the collected data. Subsequent troubleshooting ensued, working from the simplest possible optical configuration and then proceeding on one complication at a time.

• *Straight through with no sample*

It is possible to eliminate the sample by moving the analyzer to a position immediately after the modulator. This is equivalent to measuring a sample with no Kerr rotation or ellipticity. Phantom rotation can be reduced to less than about 0.01 degree by rotating the analyzer angle until the intensity signal at *2f* vanishes. Phantom ellipticity is also present in the system and is not easily prone to elimination. It has been seen as large as 0.1 degree, and as small as 0.02 degrees. Its origins are not currently understood, but the fact that this residual signal can vary from measurement to measurement suggests an alignment problem. It is found to be partially dependent upon beam alignment into the monochromator. Early suggestions were that it was dependent upon polarizer angle. Subsequent mathematical modeling of the system as well as experiment showed that this was not the case. Some examination of the effects of a retardation plate in series after the analyzer suggest that monochromator polarization dependence may somehow be playing a role. Recent experimental results of another member of our group suggest that decreased modulation amplitude will reduce phantom ellipticity.

• *Neutral sample*

No additional problems were observed when a neutral sample (an Ag or Al mirror which has negligible Kerr effect) was measured. Spectra look similar to those taken with no sample.

• *Alignment reproducibility*

The alignment technique now in use consists of mounting a neutral reference mirror in place of the sample, then rotating the analyzer until the *2f* Kerr signal is minimized. The sample to be measured is then mounted in the same place that the reference mirror was. There is some concern about the reproducibility of the plane of incidence here. If the plane rotates, it would show up as a false offset in the Kerr rotation. Test spectra on a neutral sample confirm this. A sample which is not flat may exacerbate this effect.

• *45/45 mirror problems - The twisted periscope*

The original routing scheme for getting light into the cryostat and back called for using two routing mirrors at 45 degree incidence arranged like a twisted periscope. The idea is that the both mirrors will have the same reflectivities at the same angles of incidence. S polarized light from one mirror becomes p polarized for the other, and vice versa. The overall effect is to leave the polarization state of the light intact after traversing both mirrors. A slight misalignment is inherent when the same mirrors are used to go both down and back up the mirror pair with the beam. Use of the mirrors in this fashion was abandoned when spectra could not be reliably reproduced with them between the sample and the polarization components.

• *Magnetization problems using permanent magnets*

In the absence of the superconducting magnet, $Nd_2Fe_{14}B$ permanent magnets 1cm in diameter by 1cm in length magnetized longitudinally were used in the sample mount to magnetize samples. Original manufacturer claims for this material were that fields at the surface of a 10 magnet stack would exceed 1 Tesla. Actual measurements with a Hall probe revealed that the largest applied field available from these magnets is around 6000 Oersted. This is sufficient to magnetize most of the samples we have examined so far, but usually not enough to saturate them.

Materials measured exhibiting a Kerr signal

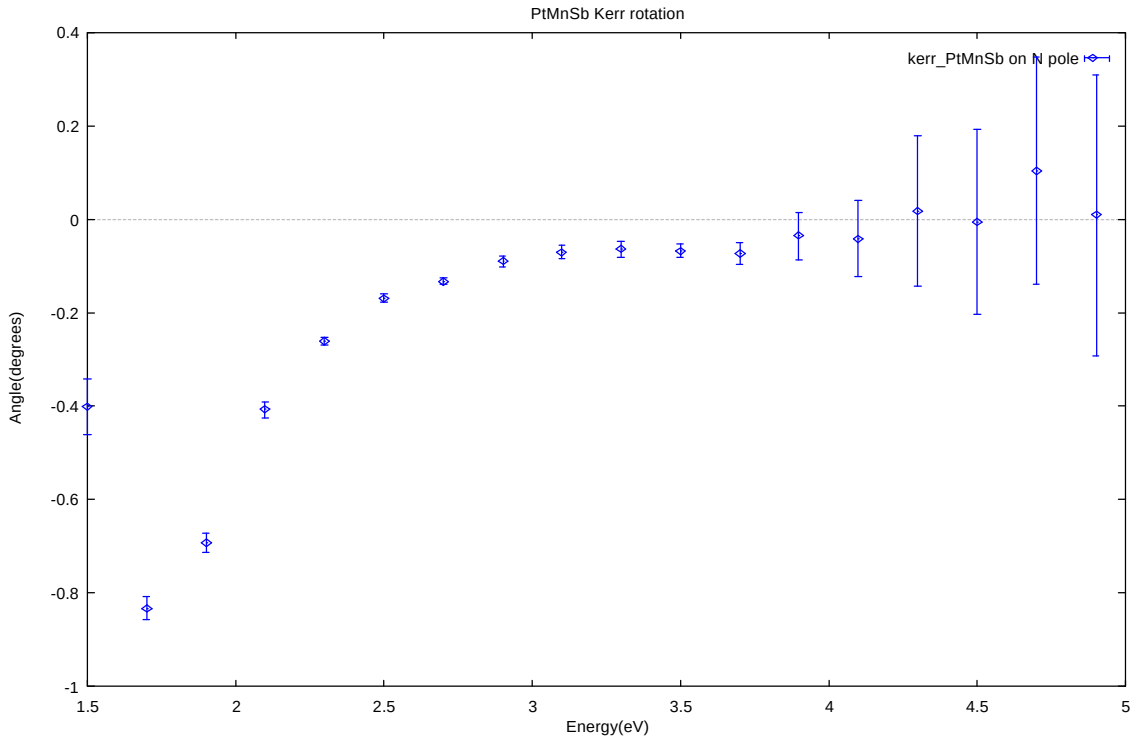
These data were all taken at room temperature in air on a permanent magnet stack.

- ***Nickel***

Data for Nickel has reproduced fairly well compared to the literature. It is important to do the correct surface preparation on this sample, or the requisite magnetic structure will be lost and the Kerr signal will not be seen.

- ***PtMnSb***

This material has a large Kerr signal. The structure of previously measured Kerr spectra were reproducible with our instrument.



- ***$Nd_2Fe_{14}B$***

We polished one of the sintered polycrystalline magnets we were using to apply our fields and measured the Kerr signal from its surface. Our data retains the structure of the published data for a polycrystalline sample, but the magnitude of the rotation is lower, presumably because the published data was taken at saturation magnetization, and ours is taken at remanent magnetization. We then measured single crystal material. A bare crystal face measured with no preparation showed reduced

Kerr rotation in the blue when compared to the polycrystalline data. The sample was then mechanically polished and re-measured. The subsequent polishing revealed a spectra similar to the polycrystalline data.

- ***$HoFe_2$***

Single crystal samples of this material with no surface preparation exhibit reasonable agreement with published data.

What's next?

The next experimental step is clearly to make measurements using the cryostat. This may be tricky due to effects from the cryostat windows. Strain birefringence due to the pressure on the vacuum window may deteriorate the polarization state of the light. This could be a big problem if the strain is not uniform across the window faces. Faraday rotation can be a significant effect near a 7 Tesla magnet. Presumably, the Faraday rotation in the windows can be calibrated and subtracted out by looking at a neutral sample in positive and negative applied fields. If these problems are overcome, the group should be well on its way to making full measurements as a function of wavelength, applied field, and temperature.

A more complete dielectric characterization of magneto-optic materials may be made by combining Kerr spectra with spectra from a spectroscopic ellipsometer. Where Kerr spectra yields information about the off-diagonal dielectric terms, the ellipsometer spectra yield the main on-diagonal parts of the dielectric tensor.